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A WAVEGUIDE SLOT SWITCHING TECHNIQUE

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C. H. Nonnemaker, Jr.

Hughes Aircraft Company
Culver City, California

Contract No. AF19(604)-8386
Project No. 4600
Task No. 460001

Scientific Report No. 5

April 1963

Prepared
for

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES
OFFICE OF AEROSPACE LABORATORIES
UNITED STATES AIR FORCE
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ABSTRACT

This report describes a series of experiments on a novel technique which permits a slot radiator in a waveguide to switch its radiation on and off by means of a compact circuit located at the plane of the slot and within the wall thickness of the waveguide feed line. As described in this report, the switching technique is applied to an end-plate series slot. It is electronically operated by means of a d.c. biased varactor diode. As a reference, the switch characteristics when operated by a mechanical tuning plunger are also given. An analytical description of the technique is also included.

The experiments were conducted at S-band and at X-band. The S-band model when operated mechanically provided a slot switching ratio of 38 db and when operated electronically gave a ratio of 35.6 db. Similar operation with an X-band model yielded 50 db and 16.1 db, respectively. These results were obtained at the original resonant frequency of the slot, i.e., the presence of the switching circuit did not change the slot resonant frequency.

Such electronically controllable slots hold promise for increasing the versatility of waveguide slot arrays. They may also find application in electronically controlled digital phase shifters.

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INTRODUCTION

Microwave antennas which are compact and can perform a variety of antenna functions would represent an invaluable asset to future space programs. In particular, a single slot-array which could be used for search and track operations as well as reconnaissance operations would be a useful tool. One approach toward achieving this versatility from a conventional slot array is by utilizing a supplementary slot control technique in the antenna system. Such a technique is the subject of this paper. Basically, the technique consists of switching <u>on</u> and <u>off</u> the slot radiation by means of a microwave control circuit which is located at the plane of the slot and within the wall thickness of the waveguide feed line. Thus, this compact slot switching configuration permits a single antenna to generate a variety of radiation patterns by selectively switching between different groups of slot radiators which are located in the common aperture wall. Another possible application of the technique would be in an iris loaded waveguide arrangement to obtain electronically controlled digital phase shifts. The following discussion describes the effect of this control circuit on an endplate series slot when the control circuit is electronically-operated (by using a d. c. biased varactor diode) and mechanically-operated (by using a movable plunger); in addition, an attempt is made to describe analytically, by means of an equivalent circuit, the operation of this device. The experimental program was conducted at S-band and at X-band. The resonant end plate slot was chosen for convenience in mechanical construction and in performing experiments. It is normally heavily coupled (unity coupled in the configurations used) and results in a low insertion loss, i. e., a high percentage of transmitted power, when on. This facilitates measurement of transmitted power levels over a wide dynamic range. The technique is also applicable to broadwall or to edge slots. The physical orientation would be different in these cases but the principles of operation would be unchanged.

TECHNICAL DISCUSSION

1. THEORETICAL CONSIDERATIONS

The slot switching technique represents a compact method of switching on and off the radiation from a slot in a waveguide. The description and operation of this device in an S-band ($f = 3.125\ G_c$) series slot located in the endplate of a rectangular waveguide is explained with the aid of Figure 1. Its physical configuration consists of a coax transmission line which is built into the wall thickness of the endplate. The coax line is terminated on one end with a variable reactance which when appropriately operated will effect the slot switching operation. The coax center conductor extends across the width of the slot in a plane which bisects the slot length and is there r-f grounded to the waveguide. In Figure 1, the r-f ground is made by an r-f coaxial choke arrangement which is used in conjunction with a varactor diode to obtain slot switching by electronic means. For the case where a movable plunger in the coax line is used (to obtain mechanical slot switching) the r-f choke can be removed and the coax center conductor physically connected to the slot wall.

For either mode of operation the coax transmission line in conjunction with the coax terminal impedance reflects a pure shunt impedance, Z_s, across the slot. The switching on and off of the slot radiation is accomplished by varying the magnitude of Z_s relative to that of the slot impedance. When Z_s reflects an open circuit across the slot the r-f currents couple maximally to the slot and the slot radiates maximum power (on-condition). For the unity-coupled series endplate slot used in this investigation, this impedance position on the Smith chart corresponds to $R/Z_o \approx 1$. Conversely when Z_s reflects a short circuit in shunt across the slot the r-f currents will couple to Z_s (and in turn be grounded) and the slot will radiate minimum power (off-condition). This position is $R/Z_o \approx 0$ on the Smith chart.

A microwave equivalent circuit for this slot switching technique at S-band (with the slot radiating into a matched rectangular waveguide rather than free space) is shown in Figure 2. The end-plate slot is

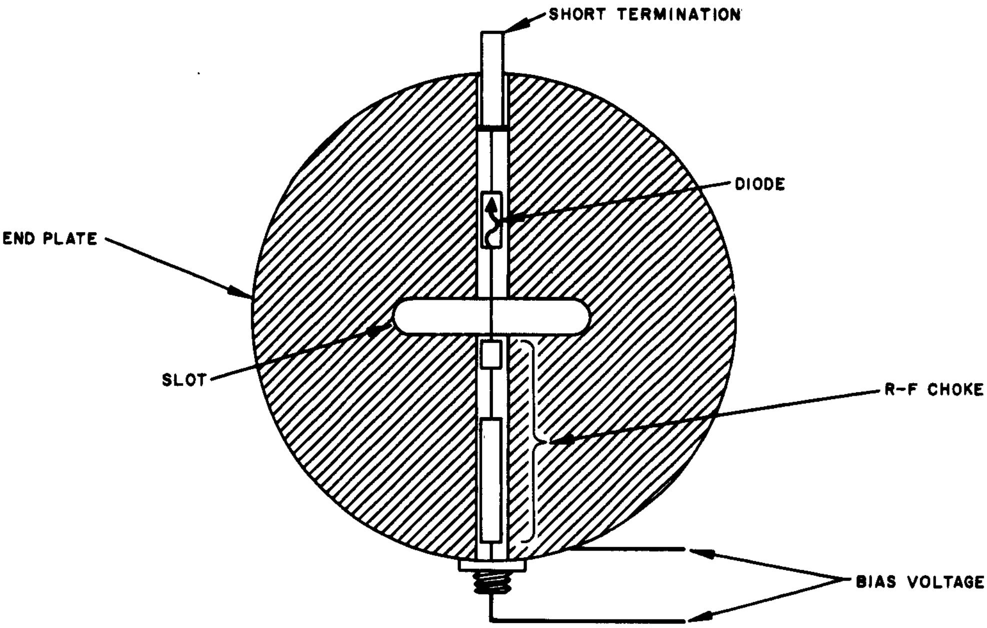


Figure 1. Schematic of slot switching configuration using a diode.

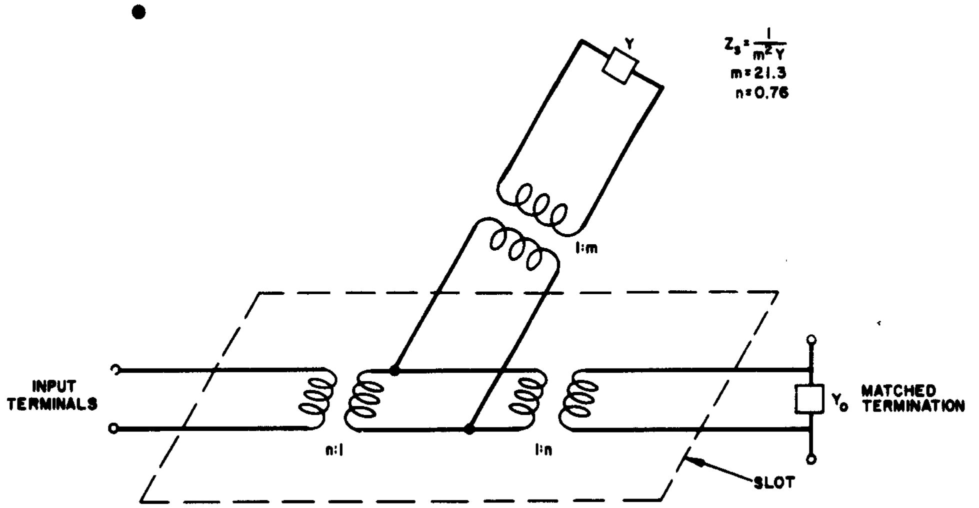


Figure 2. Microwave equivalent circuit used for endplate slot analysis.

represented by a lossless transformer with a turns ratio of n. The value for n was obtained from a scattering wave analysis of the slot behavior as described in Silver[1]. The analysis* provides an expression for the voltage transformation ratio in terms of the known parameters of the slot and waveguide. The coax transmission line loading is also represented as a lossless transformer with a turns ratio of m. The value of m was obtained empirically from the mechanical operation of the device wherein a known coax impedance termination (namely a microwave plunger) was varied and correlated with the observed input impedance changes of the device as seen in the rectangular waveguide. The transformer ratio m thus obtained was used to describe the impedance variation of the varactor diode as a function of the applied d. c. bias voltage. For convenience, an admittance analysis was used.

2. MECHANICAL SLOT SWITCHING

To demonstrate mechanical slot switching at S-band the shunt coax transmission line was terminated in a movable plunger whose admittance, Y , relative to the reference plane of the slot can be represented as,

$$Y = -j\, Y_1 \cot k(0.057 + d) \text{ mhos}, \qquad (1)$$

where Y_1 is the characteristic admittance of the coax transmission line,

$k = 2\pi/\lambda_o$ is the free space propogation constant in radians per inch, and

d is the physical displacement in inches of the face of the plunger relative to the nearest side of the slot (see Figure 3).

*See Appendix A for derivation.

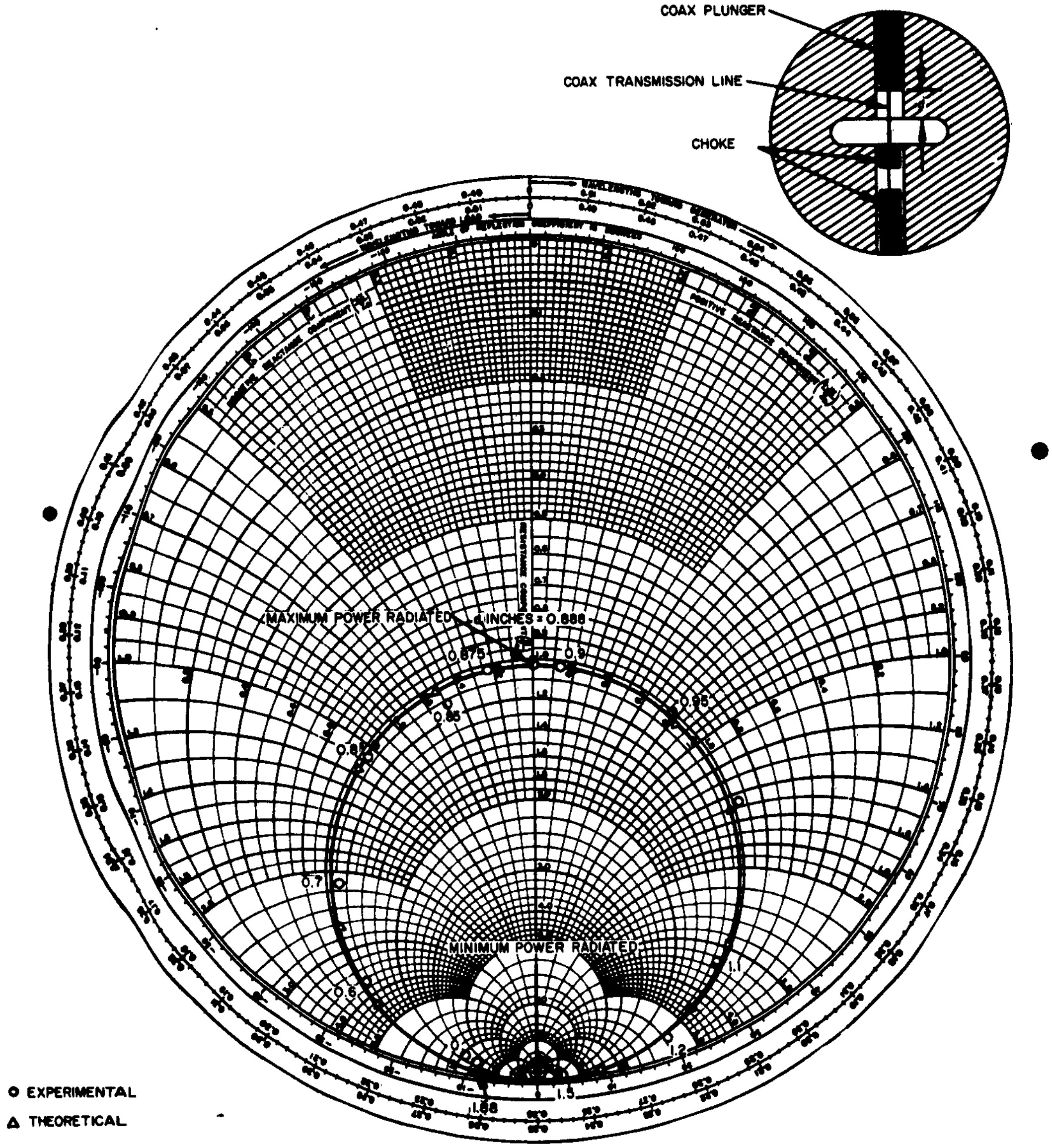


Figure 3. Admittance variation of endplate slot versus position of coax plunger, d (inches). Frequency equals 3.125 Gc. Switching ratio equals 38 db.

Using the transformer ratio m, the value of Y becomes

$$Y_s = -j\, m^2\, Y_1 \cot k(0.057 + d) \text{ mhos} \tag{2}$$

across the slot. Thus, for the equivalent circuit in Figure 2, the normalized rectangular waveguide admittance at the input terminals (the input terminals are located at some integral multiple of a half-waveguide wavelength from the plane of the slot) becomes

$$Y'_{IN} = G' + \frac{Y_s}{n^2} \text{ or}$$

$$Y'_{IN} = 1.04 - j\, 8.18 \cot k(0.057 + d) \tag{3}$$

where $G' = 1.04$ and is constant. Figure 3 shows the measured admittance variation of this device at f = 3.125 Gc. as a function of the plunger position d. Included in the figure by way of comparison are the theoretical admittance points predicted from Equation (3). The agreement is quite satisfactory over nearly the entire range of plunger movement. With the plunger positioned at d = 0.888 inches, the slot is resonant and radiates maximum power; the measured slot conductance at this on-condition position is $G' = 1.04$ which agrees quite closely with the measured G' of 1.01 when the coax circuitry is removed from the slot. Thus this technique for slot switching has little effect upon the original resonant conductance of a slot radiator and therefore can be readily incorporated into a conventional slot array design. When $d = [0.888 + \lambda o/4]$ inches the coaxial load, Y_s, reflects a short circuit in shunt across the slot and for this off-condition the slot radiates minimum power. Both the on and off conditions are repeated by moving the coax plunger back and forth $\lambda o/4$ inches. The switching ratio (S. R.), which is a measure in decibels of the power radiated for the on-condition to that for the off-condition $\left(\text{i.e., S.R. db} = 10 \log_{10} (P_{max}/P_{min})\right)$, was determined to be 38 db. The switching ratio was measured by terminating the waveguide beyond the slot by a matched detector and measuring the power received at this detector for the two conditions. A block diagram of the measuring circuit is shown in Figure 4. The S-band measuring circuit is the same as that used for electronic slot switching; this bench set-up is shown in Figure 6. The insertion loss exhibited by the mechanical slot switch was negligible.

3. ELECTRONIC SLOT SWITCHING

Having demonstrated that the slot switching technique under investigation is feasible when operated mechanically, efforts were then directed toward determining its performance when operated electronically using a voltage-controlled varactor diode as the variable impedance. With the diode placed an electrical quarter-wavelength from the reference plane of the slot in the coax line its impedance excursion (primarily due to its capacitance variation) as a function of applied d.c. bias causes the slot radiation to switch on and off. To obtain both the maximum switching ratio and the minimum insertion loss, the diode and the stationary short circuit termination in back had to be accurately positioned in the coax transmission line (see Figure 5). (The short circuit termination was used to optimize the impedance variation of the diode as seen across the slot). To locate both elements accurately, the diode and the short circuit were systematically positioned along the coax transmission line until the desired effects were optimized. The measurements were conducted with the bench apparatus shown in Figure 6. The matched detector in Figure 6 (shown detached) was attached to the end-plate slot so that accurate measurements of the power radiated by the slot could be obtained. The optimum switching ratio with minimum insertion loss was 35.6 db as shown in Figure 7 in which the isolation of the electronic slot switch is plotted as a function of diode bias voltage. Table I lists the pertinent electrical characteristics exhibited by the electronic-slot switch.

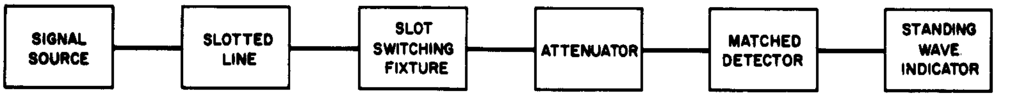
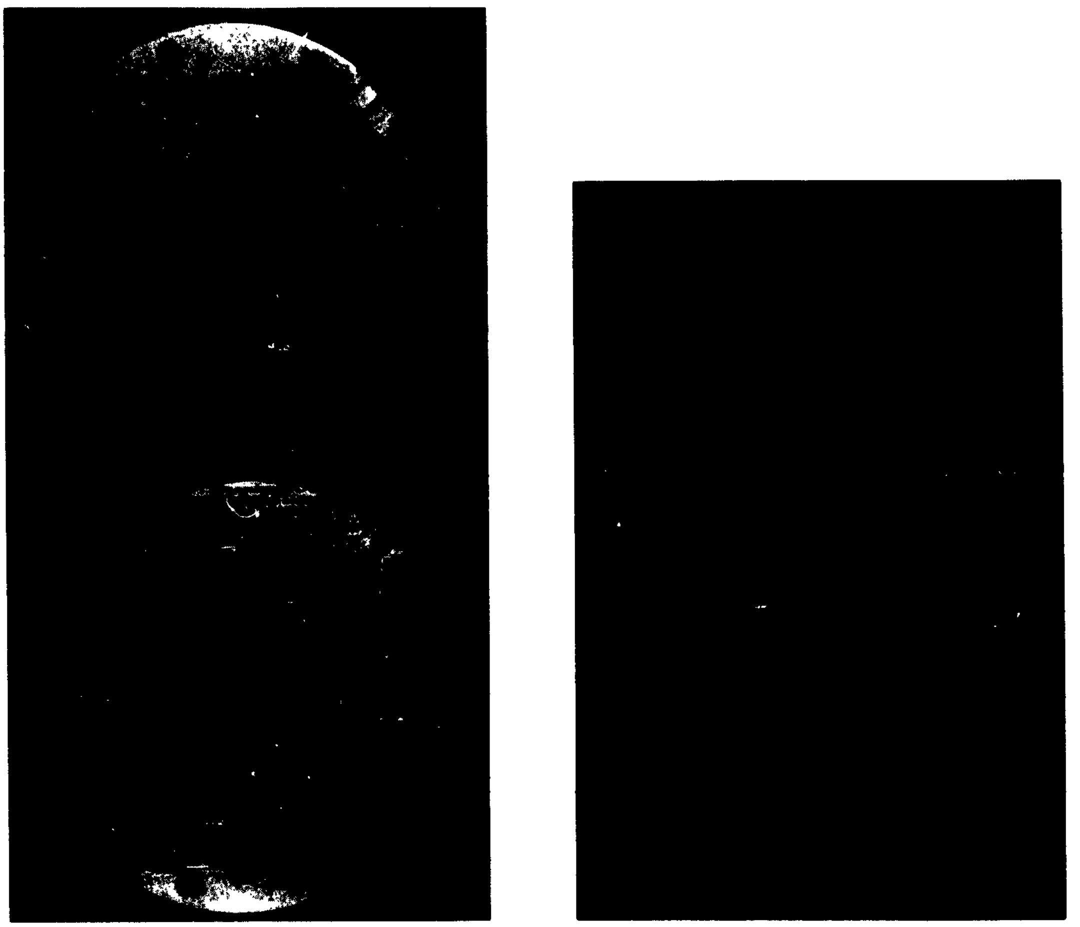


Figure 4. Block diagram of measuring apparatus.



a. Disassembled.

b. Assembled.

Figure 5. S-band diode-slot fixture.

Figure 6. S-band measuring apparatus.

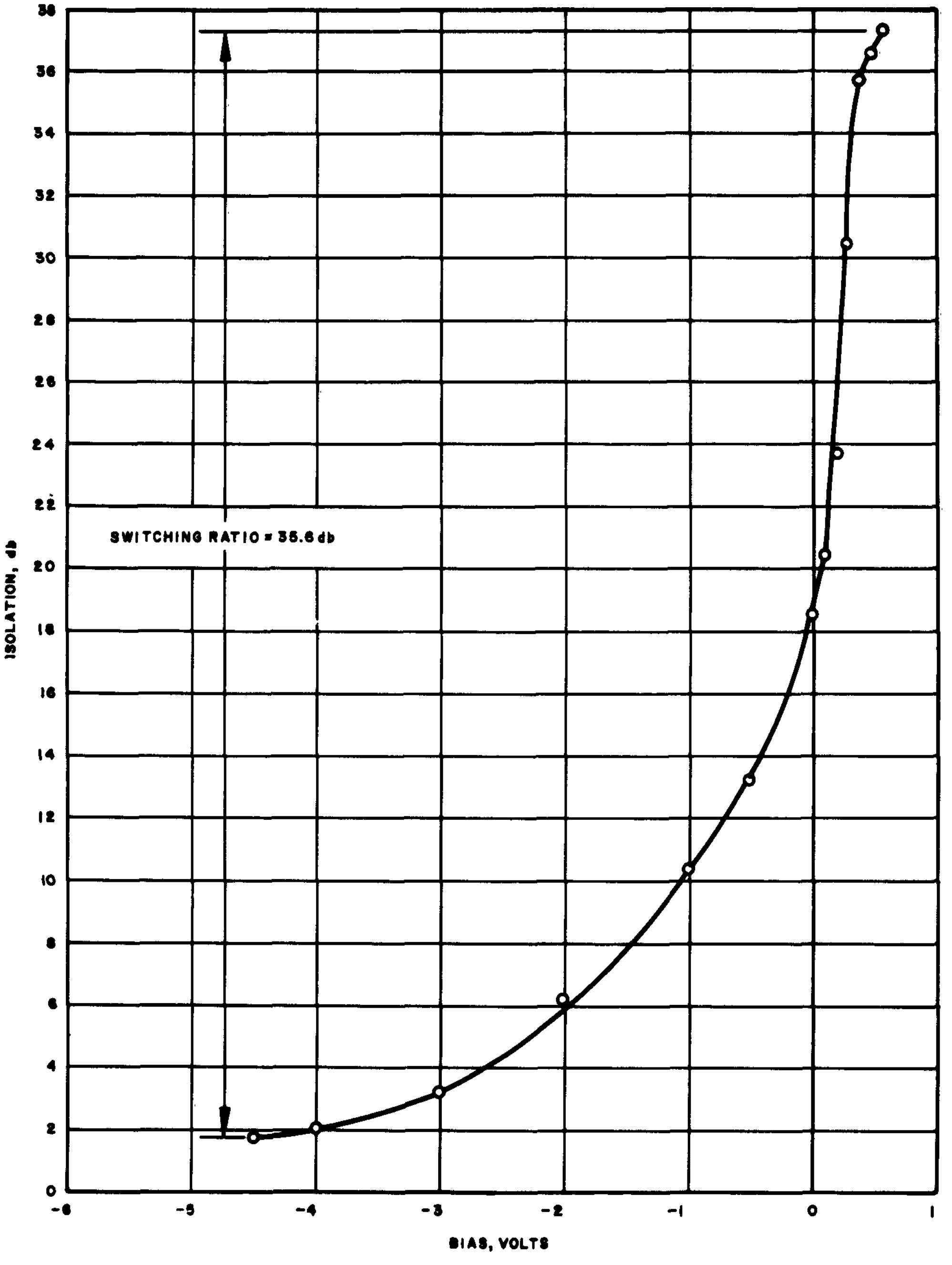


Figure 7. Isolation versus bias voltage of S-band diode-slot arrangement. Frequency equals 3.125 Gc.

Frequency (Gc)	Switch On			Switch Off	
	VSWR	Total Insertion Loss (db)	Diode and Diode Circuit Insertion Loss (db)	VSWR	Switching Ratio (db)
3.125	1.37	1.70	1.60	>50	35.6

Table I. Electrical characteristics of electronically-operated slot switch.

Figure 8 shows the admittance variation of the slot as a function of diode bias voltage. These results are typical of the performance obtained with several S-band diodes which were positioned as shown in the insert in Figure 8.

The diodes used at S-band were Hughes gold-bonded germanium varactor diodes type 1N896[2]. Their characteristics are: a zero bias junction capacitance of about 2 pf, a stray capacitance of about 0.2 pf, a reverse voltage of at least 5 volts and a frequency cut-off of 30 Gc or higher at operating bias. Frequency cut-off ranges as high as 100 Gc at maximum reverse bias. The series resistance, $\underline{R_s}$, in reverse bias is between 4 and 5 ohms.

For the diode and short termination arrangement shown in the insert of Figure 8 the admittance, Y_s, across the slot is given by

$$Y_s = m^2 \, Y_1^{\,2} \, Z_{DIODE} \text{ mhos} \tag{4}$$

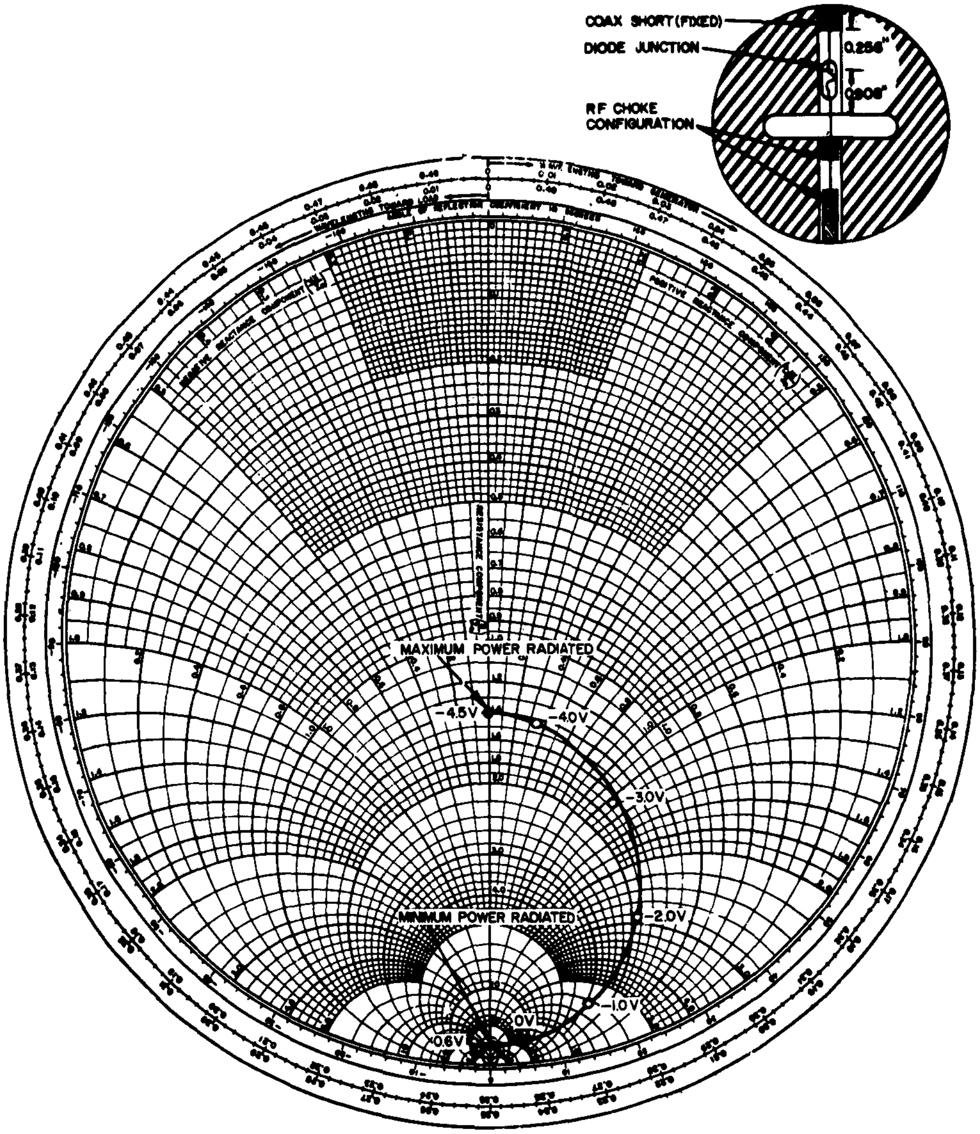


Figure 8. Admittance variation of endplate slot versus applied diode bias voltage. Frequency equals 3.125 Gc. Switching ratio equals 35.6 db.

wherein it is assumed that the diode junction is located an electrical quarter free space wavelength from the reference plane of the slot and the short termination is effectively in the reference plane of the diode junction; the value of the transformer ratio m is the same as that used in the mechanical slot switch analysis. Equation (4) is a semi-quantitative expression since it is based upon assumptions that have not been checked experimentally by measurements in the coax transmission line. Experimentation to determine the impedance variation and reference plane of the diode and short circuit termination within the coax transmission line was found to be difficult because of the physical size of the coax line. Thus, it was decided to optimize the electronic slot switch performance by systematically locating the appropriate electrical positions for the diode and short termination.

To check the validity of Equation (4) the admittance variation data in Figure 8 were used with the predicted admittance expression of the electronically-operated endplate slot,

$$Y'_{IN} = 1.04 + \left(\frac{m\, Y_1}{n}\right)^2 Z_{DIODE}, \tag{5}$$

to compute the impedance variation of the diode for reverse bias voltages. The diode impedance as a function of applied reverse voltage, v, was represented by,

$$Z_{DIODE}(v) = R_s(v) + j\left(111 - \frac{1}{\omega\, C_j(v)}\right) \text{ohms}, \tag{6}$$

where R_s is the spreading resistance or loss factor of the diode,

C_j is the junction capacitance of the diode, and

$\omega = 2\pi f$, $f = 3.125$ Gc.

The constant inductive reactance of 111 ohms is due in part at least to the fact that effective position of the short circuit termination was not exactly in the diode reference plane. The value for this inductive reactance was determined empirically from the slot admittance plot in Figure 8. On using Equation 6 and numerically evaluating the constants, Equation 5 becomes,

$$Y'_{IN}(v) = \left[1.04 + 0.0845\ R_s(v)\right] + j\left[0.0845\left(111 - \frac{51}{C_j(v)}\right)\right], \qquad (7)$$

where $C_j(v)$ is given in pico farads. Using Equation (7) and the admittance data in Figure 8 the diode impedance variation was calculated in terms of $R_s(v)$ and $C_j(v)$. These results are given in Table II below.

Diode Bias Voltage, v (Volts)	Diode Spreading Resistance, R_s (Ohms)	Total Diode Capacitance	
		$C = C_j + 0.2^*$	(Pico farads)
-4.5	4.3 (4.1)	0.66	
-4.0	4.3	0.68	(0.66)
-3.0	6.4	0.73	(0.74)
-2.0	10.2	0.87	(0.86)
-1.0	11.2	1.5	(1.04)

*A stray capacitance of 0.2 pico farads is included in the total capacitance values given above; the value is consistent with the available data on these diodes.

Table II. Computed diode parameters. Typical total capacitance values for these diodes are given in brackets.

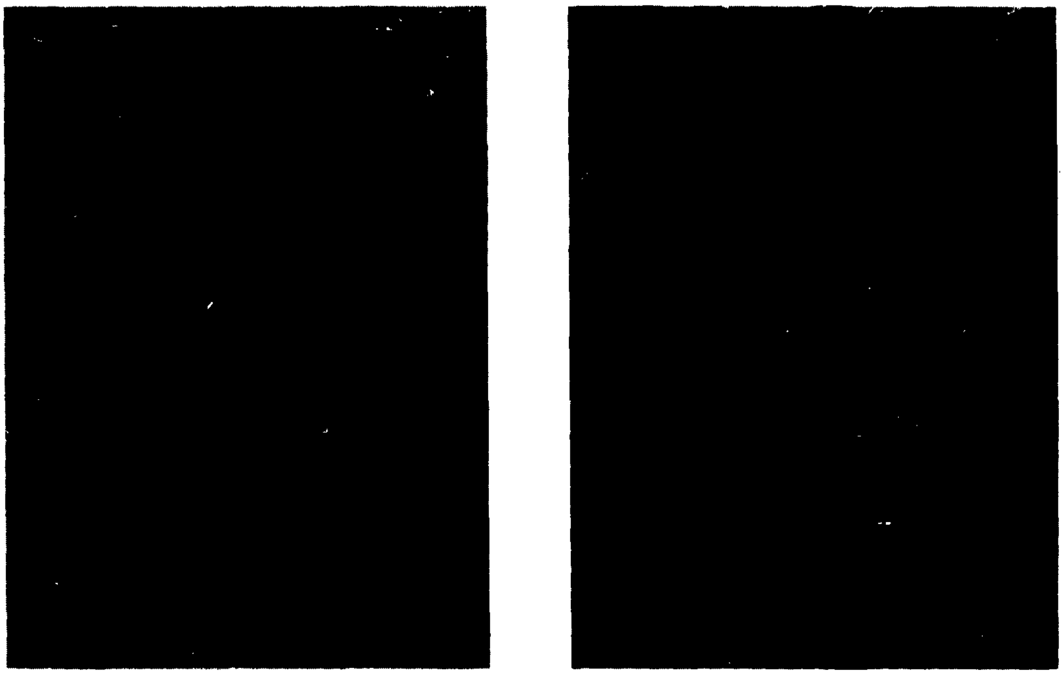
It must again be pointed out that the data given in Table II are semi-quantitative in value because measurements of the effective diode and short circuit positions were not made directly in the coaxial line.

When considered as such, the data are in good agreement with that predicted. The variation in capacitance and the magnitude of the capacitance values agree satisfactorily. The spreading resistance, R_s, was observed to increase by a factor of 2.6 as the bias voltage approached forward bias. Although limited information is available on R_s for these diodes, previous work with the same type diode at X-band indicates that their R_s does increase (i.e. they become more lossy) as the diodes are more positively-biased.[3] The value of R_s at -4.5 volts agrees quite satisfactorily with that predicted (4.1 ohms) from the Application Engineering Notes brochure.[2] Thus, Equation 4 can be used to represent the net admittance of the diode circuit across the slot.

4. SLOT SWITCHING RESULTS AT X-BAND

In addition to the work performed at S-band some measurements were also conducted with this type device at X-band (f = 9.130 Gc). These results will now be given. The endplate series slot that was constructed is shown in Figure 9. The observed admittance variation of the device when operated mechanically and electronically is given in Figure 10. The mechanical switching ratio was 50 db; the resonant conductance of the slot for the on-condition was identical to its resonant conductance without the coax transmission line being present. This result shows that the presence of the coax circuit does not detune the slot for the on-condition or maximum slot radiation condition. Electronic operation of this device provided a switching ratio of 16.1 db. Other pertinent characteristics of the electronic-operated slot switch are given in Table III; Figure 11 shows the isolation of the device as a function of diode bias voltage. The X-band diode used to obtain these results was a Sylvania silicon epitaxial mesa type D4909A.

The experimentation at X-band was primarily undertaken to demonstrate that this slot switching technique could be extended to this



a. Disassembled.　　　b. Assembled.

Figure 9. X-band endplate slot configuration.

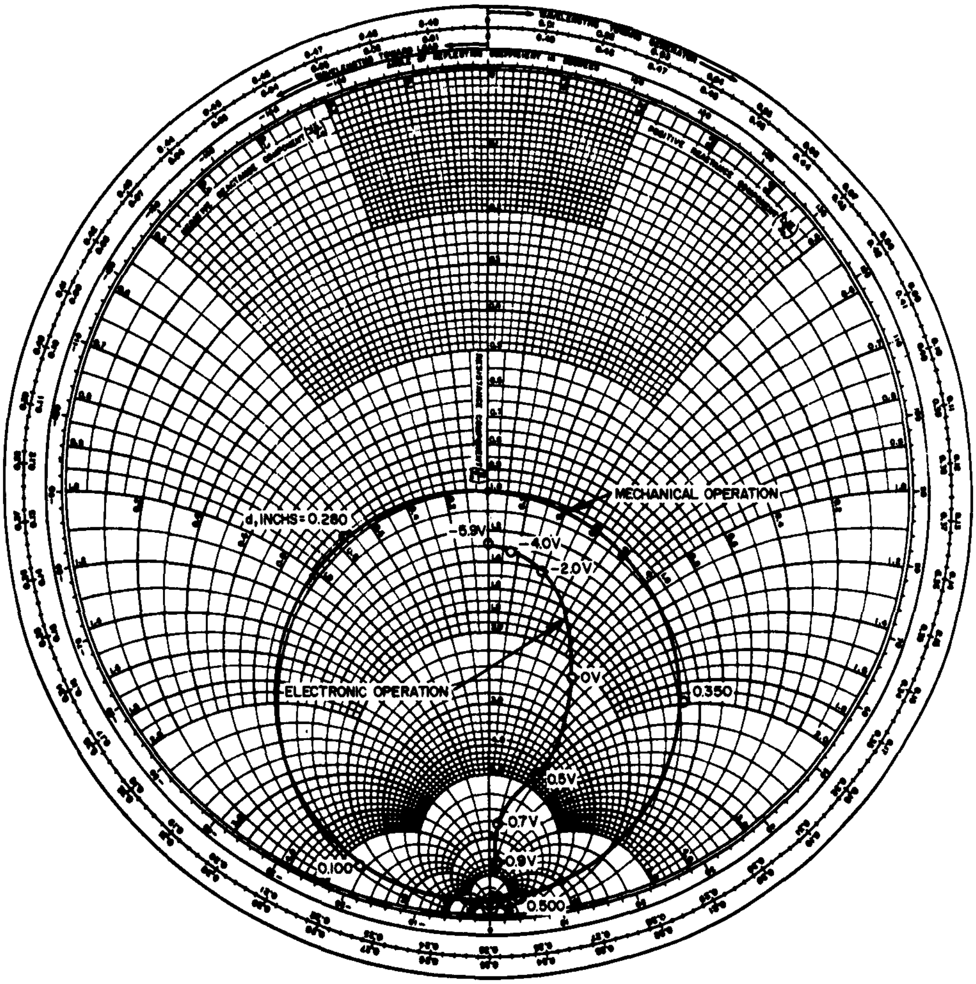


Figure 10. Admittance variation of X-band endplate slot. Frequency equals 9.130 Gc. Mechanical switching ratio equals 50 db. Electrical switching ratio equals 16.1 db.

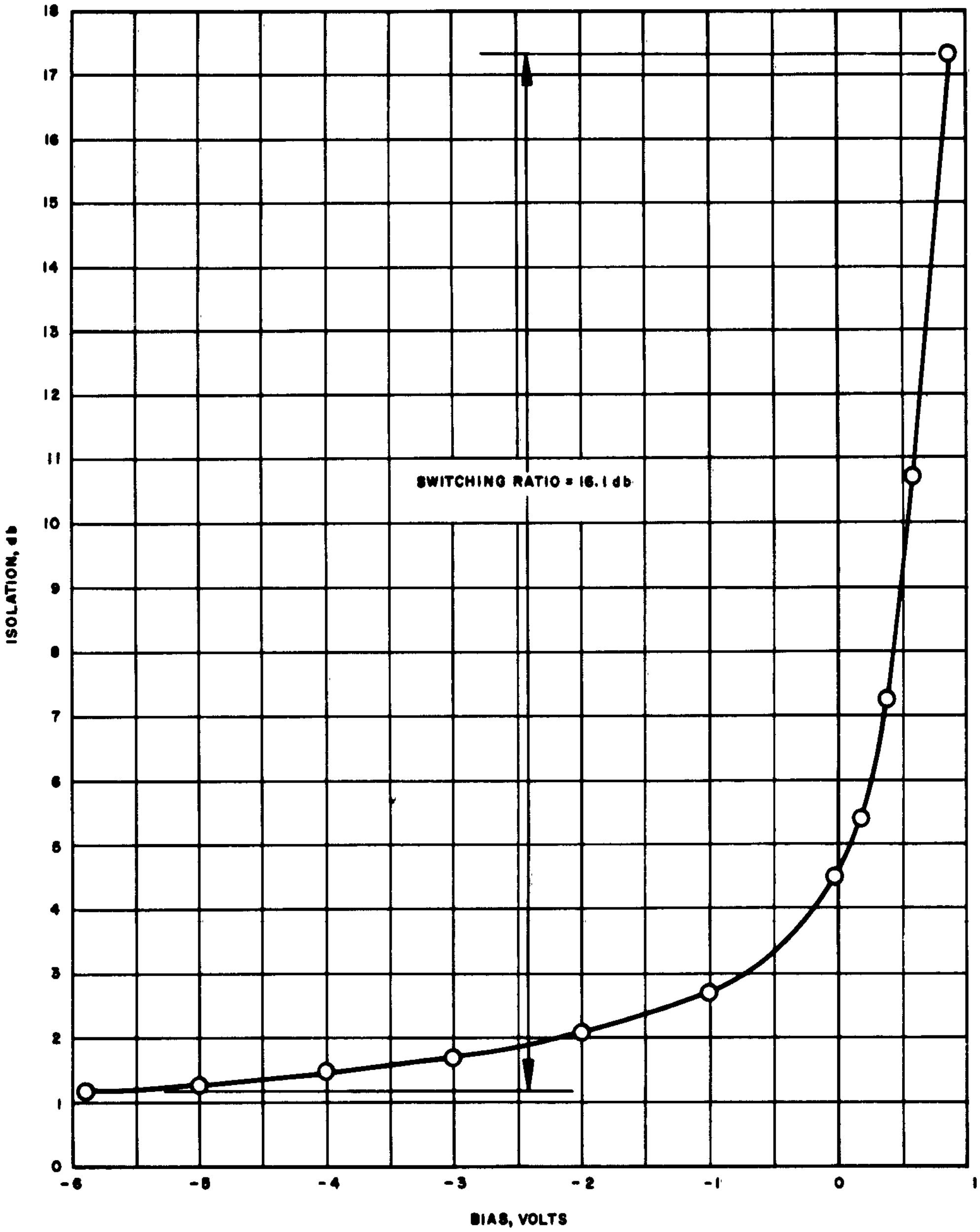


Figure 11. Isolation versus bias voltage of X-band diode-slot arrangement. Frequency equals 9.130 Gc.

	SWITCH ON			SWITCH OFF	
Frequency (Gc)	VSWR	Total Insertion Loss (db)	Diode and diode circuit insertion loss (db)	VSWR	SWITCHING RATIO (db)
9.130	1.29	1.2	1.1	13.8	16.1

Table III. Electrical characteristics of electronically-operated slot switch.

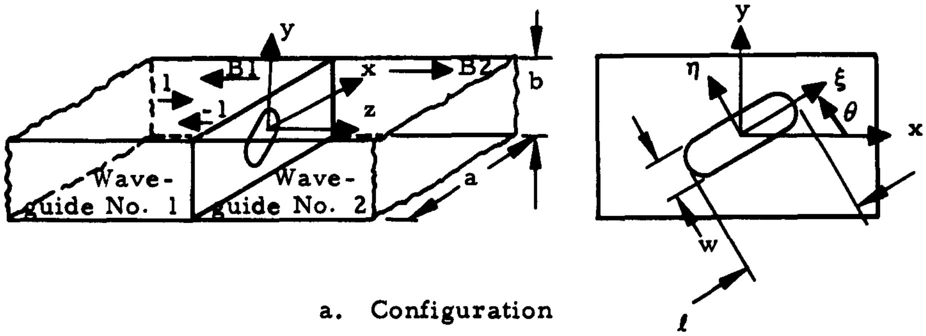
higher frequency range. The initial results obtained are encouraging and indicate that a practical electronically-driven device can be realized.

CONCLUSIONS

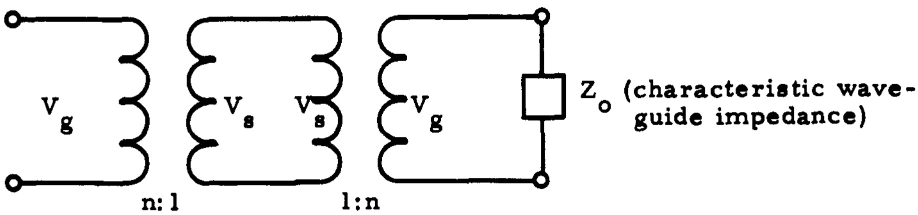
This paper has described a slot switching technique which can eventually have application in a space antenna system. The scope of the investigation was limited to its performance in an endplate series slot. Mechanical and electronic operation of the technique has been demonstrated at S-band and X-band. However, further development of the technique is required. Suggested areas for further development work should include: 1) A quantitative investigation of the diode impedance behavior in the coax transmission line circuit to ascertain optimum performance, 2) A study of diodes to determine their optimum characteristics for this application and, 3) An investigation of switching times and power handling capability with this technique.

APPENDIX A

THE DETERMINATION OF THE TRANSFORMER RATIO "n"



a. Configuration



b. Equivalent Circuit

Figure A-1. Endplate series-series waveguide coupler.

Consider a TE_{10} - wave of amplitude unity in waveguide No. 1 to be incident on the slot from the left as shown in Figure A-1; this field induces a voltage across the slot which causes the slot to back-scatter a wave of amplitude B_1 into waveguide No. 1 and to forward-scatter a wave of amplitude B_2 into waveguide No. 2.

For identical waveguides, $B_1 = B_2 = B$, and the B can be evaluated from

$$B = - \frac{1}{2S_{10}} \int_{SLOT} (\bar{E}_1 \times \bar{H}_2) \cdot \hat{e}_z \, da \tag{A-1}$$

where

$$\overline{E}_1 = \overline{E}_\eta = \hat{e}_\eta E_o \cos\left(\frac{\pi}{\ell}\xi\right)$$

is the electric field generated within the slot,

$$\overline{H}_2 = -2Y_{10} \cos\left(\frac{\pi\cos\theta}{a}\xi\right)\left\{\hat{e}_\xi \cos\theta - \hat{e}_\eta \sin\theta\right\}$$

is twice the mode magnetic field component in the X-direction expressed in terms of the slot coordinate system [Y_{10} is the waveguide characteristic admittance for the dominant mode]*, and S_{10} is twice the Poynting energy flux for the dominant waveguide mode.

Performing the integration, one gets

$$B = \frac{2w\, E_o\, Y_{10}}{S_{10}} \left\{ \frac{\ell \cos\left(\frac{\pi\cos\theta}{2a}\ell\right)}{\pi\left\{1 - \left(\frac{\ell\cos\theta}{a}\right)^2\right\}} \right\} \cos\theta \qquad \text{(A-2)}$$

where $\underline{\ell}$ is the length of the slot, and

$\underline{w}$ is the width of the slot.

Let us define the voltage across the slot at its center to be

$$V_s = W\, E_o \quad \text{and} \qquad \text{(A-3)}$$

*The field components of the TE_{10} mode have been normalized so that the amplitude of the peak electric field component is unity, i.e., $E_y = \cos(\pi x/a)$.

the voltage of the scattered wave at the center in either waveguide as

$$V_g = b\,B \tag{A-4}$$

then the voltage transformation ratio <u>n</u> becomes

$$n = \frac{V_g}{V_s} = \frac{4}{a}\left\{ \frac{\ell \cos\left(\frac{\pi \cos\theta}{2a}\,\ell\right)}{\pi\left\{1 - \left(\frac{\ell\cos\theta}{a}\right)^2\right\}} \right\} \cos\theta\ . \tag{A-5}$$

For the series slot used in this investigation $\theta = 0^\circ$ and $\ell = \lambda_o/2$; Equation (5) therefore reduces to

$$n = \frac{2}{\pi a}\left(\frac{\lambda_g^{\;2}}{\lambda_o}\right) \cos\left(\frac{\pi\,\lambda_o}{4a}\right) \tag{A-6}$$

which when numerically evaluated at $f = 3.125$ Gc, $a = 2.84$ inches (standard S-band waveguide dimension) becomes $n = 0.76$.

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April 1963. 24 pages including illus., 3 refs.
Scientific Report No. 5, Contract AF19(604)-8386
Project No. 4600 Task No. 460001

Unclassified Report

This report describes a series of experiments on a novel technique which permits a slot radiator in a waveguide to switch its radiation on and off by means of a compact circuit located at the plane of the slot and within the wall thickness of the waveguide feed line. As described in this report, the switching technique is applied to an endplate series slot. It is electronically operated by means of a d.c. biased varactor diode. As a reference, the switch characteristics when operated by a mechanical tuning plunger are also given. An analytical description of the technique is also included. The experiments were conducted at S-band and at X-band. The S-band model when operated mechanically provided a slot switching ratio of 38 db and when operated electronically gave a ratio of 35.6 db. Similar operation with an X-band model yielded 50 db and 16.1 db, respectively. These results were obtained at the original resonant frequency.

Such electronically controllable slots hold promise for increasing the versatility of waveguide slot arrays. They may also find application in electronically controlled digital phase shifters.

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4. Slot switching results at X-band
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